

Outflows and jets from massive star-forming clusters

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Abstract

Studying outflows from young massive star-forming clusters allows one to deduce physical processes that lead to the formation of the most massive stars. I will review the current state of high-spatial-resolution interferometric (sub-)mm studies of massive molecular outflows and their implications for high-mass star formation. A possible evolutionary scenario for massive outflows with highly collimated structures at the very beginning and more wind-like outflows at later stages will be outlined.

1 Introduction

Most of the subjects and contributions to this conference focus on the radio and/or X-ray regime of the electromagnetic spectrum. While these two regimes are the extremes from the observational point of view, many processes are best observed between these frequencies. The youngest massive star-forming regions are typically cold and dominated by thermal emission at temperatures between 10 and 100 K which peak at mm/sub-mm wavelengths. Therefore, the study of jets and outflows from such regions has to concentrate on this wavelength regime, and regarding the title of the conference I will focus on the “*connection*”.

One of the best known outflows in massive star formation is the chaotic outflow system emanating from the Orion-KL region. Morphologically, it appears very different from typical collimated low-mass outflows because it does not show any preferred direction and resembles an explosion-like scenario (see, e.g., near-infrared images by Schultz et al. 1999). It is important to stress that this well known outflow is far from being typical, and studies of other massive outflows – as discussed below – indicate that the Orion outflow might even be the exception. In the following, I will concen-

trate on outflows and jets of massive star-forming regions at early evolutionary stages prior or at the beginning of forming an ultracompact HII (UCHII) region.

Massive star formation proceeds in a clustered mode, and due to large typical distances of a few kpc it is difficult to resolve the cluster centers spatially in the (sub-)mm regime (see, e.g., various reviews in *Protostars and Planets IV*). Even with the most advanced interferometric imaging techniques we rarely exceed a linear spatial resolution of a few 1000 AU. An alternative approach to study the formation of massive stars is to investigate the properties of the molecular outflows and jets. These outflows take place on parsec scales, they are far easier to resolve spatially and indirectly give information about the physical processes taking place at the cluster centers.

Mainly two scenarios compete to explain the formation of massive stars: on the one hand, the low-mass paradigm is extended to high-mass stars, and the most massive objects can form via similar accretion-based processes as their low-mass counterparts, just with significantly enhanced accretion rates (e.g., Wolfire & Cassinelli 1987; Jijina & Adams 1996; McKee & Tan 2003; Yorke & Sonnhalter 2002). On the other hand, it was proposed that massive stars could also form at the center of very dense clusters by mergers of intermediate-mass protostars (e.g., Bonnell et al. 1998; Stahler et al. 2000; Bally 2002). Outflow studies can help to discriminate between the two scenarios because the accretion-based formation requires massive outflows as collimated as their low-mass counterparts, whereas the coalescence scenario predicts outflows to be far less collimated.

2 Single-dish studies

Most single-dish studies of massive molecular outflows agree that they are ubiquitous phenomena in high-mass star formation and that they are far more massive and energetic than their low-mass counterparts (Shepherd & Churchwell 1996b; Richer et al. 2000; Ridge & Moore 2001; Zhang et al. 2001; Beuther et al. 2002c). However, early single-dish studies of massive outflows indicated that they might be less collimated than low-mass outflows (Shepherd & Churchwell 1996a; Ridge & Moore 2001). This led to the conclusion that different physical processes might entrain the molecular gas, e.g., the deflection of infalling gas from the massive protostar (Churchwell 1999). Furthermore, these results were interpreted as support for the coalescence scenario.

Contrary to this, more recent single-dish observations by Beuther et al. (2002c) with an angular resolution up to 5 times better than previous studies show that the previously observed lower collimation of massive outflows might only be an observational artifact due to the larger distances of the outflows. Their sample of 21 bipolar outflows is consistent with massive outflows being as collimated as low-mass flows, and thus support the accretion scenario.

Obviously, single-dish studies allow ambiguous interpretations and only high-spatial resolution interferometric studies of massive outflows can shed light on the underlying outflow and star formation processes.

3 High-spatial-resolution studies

Over the last few years interferometric studies of massive outflows developed a more detailed picture of their properties. Figure 1 shows as an example the various molecular outflows toward the young high-mass protostellar object (HMPO) IRAS 05358+3543 that is in an evolutionary stage prior to forming an UCHII region (Beuther et al. 2002b).

The main feature in Figure 1(a) is the highly collimated molecular CO(1–0) outflow emanating from a $100 M_{\odot}$ dust condensation and terminating in bowshocks observed in H_2 emission. The collimation degree (length divided by width) of this outflow is 10 – as high as the highest values reported for low-mass flows (Richer et al. 2000) –, and the mass of entrained gas is $\sim 10 M_{\odot}$. From the outflow rate we can estimate an accretion rate for the central object of the order a

few times $10^{-4} M_{\odot}/\text{yr}$. About $30''$ to the west, we observe a second outflow which is easier depicted in the SiO(2–1) emission in Figure 1(b). For this flow, we do not detect a driving source in the mm continuum (mass sensitivity $\sim 50 M_{\odot}$), but the simultaneously observed $H^{13}\text{CO}^+(1-0)$ data show two peaks near the outflow center, one of which likely harbors the driving source. In addition to these two outflows, we detect a third high-velocity gas outflow emanating again from the main $100 M_{\odot}$ dust condensation at a position angle of 45° with respect to the collimated large-scale outflow (see the inset in Figure 1). A detailed analysis of the whole region can be found in Beuther et al. (2002b).

The bolometric luminosity of this source is $10^{3.8} L_{\odot}$ corresponding to a B1 star, thus we have not reached the regime of genuine O stars yet. Nevertheless, the data show that very young stars greater $10 M_{\odot}$ can exhibit massive and collimated outflows, and the estimated accretion rate is consistent with the accretion-based formation of massive stars (e.g., Norberg & Maeder 2000; McKee & Tan 2003). Contrary to this, it is hard to imagine how such a collimated structure could survive during the highly energetic and eruptive processes of potential protostellar mergers. The overall picture of this region appears to be complicated due to the clustered mode of formation, several protostellar condensations and outflows, but with high enough spatial resolution we can disentangle the region into features well known from low-mass star formation, new physical processes like protostellar mergers are not necessary. Similar results were obtained via mm interferometer studies by, e.g., Beuther et al. (2003); Gibb et al. (2003); Su et al. (2004); Wyrowski et al. (in prep.). Tackling the problem from the near-infrared, some groups started studying the shocked H_2 emission at $2.1 \mu\text{m}$, and, e.g., Davis et al. (in prep.) also conclude from their H_2 observations that the molecular jets they observe are scaled-up versions of their low-mass counterparts.

However, not all observed massive outflows fit as well into this scenario. For example, Shepherd et al. (1998) observed the massive outflow toward the UCHII region G192.16, and they find an opening angle of the outflow of 60° (Fig. 2). This outflow is consistent with both – the presence of a poorly collimated wind and a jet (Shepherd et al. 1998). Additional studies of outflows toward UCHII regions in W75 (Shepherd et al. 2003)

Figure 1: Presented are the PdBI observations as contour overlays on the grey-scale H_2 data (Beuther et al. 2002b). The blue and red lines in Figures (a) & (b) show the blue and red wing emission of the CO(1–0) and SiO(2–1) emission, respectively. The green lines in Figure (c) present the integrated $H^{13}CO^+(1-0)$ emission. The numbers in brackets label the three $H^{13}CO^+$ sources and the beams are shown at the bottom right. In all images the arrows and ellipses sketch the three outflows (the arrows to the right and the ellipses represent two slightly different interpretations of the western outflow). The three squares represent the three mm sources, the diamonds locate the $H^{13}CO^+$ peaks, and the triangle marks the IRAS 12 μm position. The inset at the top-left shows a close-up of the central 3 mm sources (grey-scale) and the high-velocity outflow.

also indicate that these massive outflows are not just scaled-up version of low-mass flows.

Position-velocity (p-v) diagrams: In addition to morphological interpretations of massive outflows it is important to study their kinematics as well. Beuther et al. (2004) compared the p-v diagrams of four massive outflows, ranging in luminosity from intermediate-mass protostars to high-mass regions with $10^{4.9} L_{\odot}$, with previous studies in the low-mass regime by Lee et al. (2000, 2002). The various p-v diagrams are shown in Figure 3, and we can discern various features: in some sources, we detect high-velocity gas at the center (IRAS 19217, IRAS 20293, IRAS 23033), whereas we detect high-velocity gas at some distance from the outflow center in all regions but with various signatures: IRAS 23033 exhibits the well-known Hubble-law, i.e. a velocity increase with distance from the outflow center; in IRAS 20293 the end of the outflow shows emission at all velocities; and IRAS 19217 shows some high-velocity features but without any real symmetry with regard to the core center; the p-v diagram toward IRAS 20126 is very symmetric showing first increasing and then decreasing velocities with distance from the core center.

The variety of different features in the p-v plane is broad, but comparing them to low-mass studies, the same features appear in p-v diagrams for sources of all masses. Lee et al. (2000, 2001, 2002) model the different features by wind-driven outflows on the one hand and jet-driven outflows on the other hand. No single model can reproduce all observations consistently. Therefore, they conclude that outflows can be driven by both processes, in most sources one or the other process is dominant but sometimes wind- and jet-driven contributions can be observed within the same outflow. Apparently, this statement also holds for high-mass stars, we observe jet-like morphologies and corresponding features in the p-v domain as well as wind-like less collimated outflows and their corresponding p-v signatures.

Evolutionary sequence? The statistical number of observed massive outflows with sufficiently high angular resolution is still poor, but considering the evolutionary state of different sources some tentative interpretations are possible. The most collimated jet-like massive outflows have been observed toward the earliest stages of massive star formation, the so called HMPOs which have not yet formed any UCHII region (e.g., IRAS 05358+3543), whereas the less collimated and more wind-like outflows were detected toward slightly more evolved UCHII regions (e.g., W75). This evolutionary difference triggers the speculation that the various observed outflow morphologies and p-v diagrams could be due to the evolution of the underlying massive protostar.

In this scenario, at the earliest stages massive protostars should be surrounded by massive accretion disks and drive collimated jet-like outflows as observed toward their low-mass counterparts. Shortly after the central protostar ignites, we observe an UCHII region and the stellar wind contributes a less collimated component to the outflow. During the following evolution, the disk and the jet-like outflow are unlikely to survive and only the wide-angle wind-like outflow remains observable.

As the evolutionary timescales get shorter the more massive the stars are, it is likely that the timescale for jet-like outflows in evolving early O stars should be extremely short, whereas collimated outflows should be observable significantly longer toward early B stars. This could also explain that we do observe collimated outflows toward B stars like IRAS 05358+3543 whereas we were not yet successful in finding any toward genuine early O stars. In this scenario, it will be highly difficult to observe collimated outflows toward early O stars just because they are rare and the corresponding evolutionary stage so short-lived.

Furthermore, during the formation of an O star, the protostellar region exhibits for some time *only* the luminosity of a B star, and that could be just the time

Figure 2: The blue and red CO(1–0) emission toward G192.16 observed with OVRO (Shepherd et al. 1998). The inset shows a close-up of the central mm continuum driving source. The synthesized beams are shown at the bottom left/right of each panel.

Figure 3: Position-velocity diagrams of the four intermediate- to high-mass outflows presented in Beuther et al. (2004). The horizontal lines mark the centers of the outflows which always correspond to the main mm continuum sources. At the top left of each panel we show the resolution element.

where we can observe the collimated outflows. Accreting further and reaching the luminosity of an O star the radiation and wind of the evolving central driving source can already be so strong that it dominates any previously observable collimated structures. In that framework, it could be intrinsically impossible to ever observe a collimated outflow from an O star because collimated structures would only exist in the phase when the source has not reached its O star luminosity yet.

4 The Xray and radio regime

As mentioned in the introduction, this contribution focuses’ mainly on the (sub-)mm regime, thus the “*connection*” of the Xray and radio wavelengths. Nevertheless, I will shortly discuss what we can learn from Xray and radio observations of massive outflows and jets.

Xray: Regarding Xray observations, the discussion remains short because so far there have been no detections of any outflow features in the Xray regime toward very young massive star-forming regions. There are studies toward various regions of massive star formation (Orion, Garmire et al. 2000; W3, Hofner et al. 2002; IRAS 19410+2336, Beuther et al. 2002a), and many point sources were detected in each of the fields, but no emission clearly associated with molecular outflows or jets. The situation is slightly different for more evolved massive star-forming regions, and Townsley et al. (2003) detect diffuse soft Xray emission toward a number of regions. This emission likely arises from fast O star winds thermalized either by wind-wind collisions or by a termination shock against the surrounding media. More details can be found in this volume’s contribution by Leisa Townsley. At the low-mass end of molecular outflows there are few detections of Xray emission toward bow-shocks (e.g., in L1551, Favata et al. 2002) but these are also rare.

Radio: Contrary to the Xray-regime, there are numerous observations of radio jets toward massive star-forming regions. Figure 4 shows two examples, the

left one a typical thermal radio jet, and to the right the unique case of a synchrotron jet in star formation.

The most commonly observed radio jets have a positive spectral index due to a partially optically thick thermal free-free emission (Anglada et al. 1998). The spatial extent of these radio jets is always very small – a few arc-seconds – compared to the large scale molecular outflows discussed in the previous section. These radio jets are likely to be at the base of the large-scale outflows observed at (sub-)mm wavelengths.

While thermal radio jets are typical, the radio jet in W3(H₂O) exhibits a negative spectral index (Reid et al. 1995) consistent with synchrotron emission. While synchrotron jets are observed regularly toward external galaxies, this is the only known synchrotron jet emanating from a star-forming region. The 1.6 GHz flux of 2.5 mJy can be extrapolated to the Xray-regime ($S \propto \nu^{-0.6}$) and the expected flux at 3 keV would be $0.02 \mu\text{Jy} \sim 2 \times 10^{-23} \text{ erg cm}^{-2}$, too weak to be detected by CHANDRA or XMM. Recently, Shchekinov & Soboloev (2004) modeled the synchrotron emission of W3H₂O via the interaction of a stellar wind with the surface of a circumstellar accretion disk.

An interesting but likely circumstantial difference between the thermal radio jet in Cepheus A and the synchrotron jet in W3(H₂O) is the associated H₂O maser emission. While the H₂O masers in Cepheus A are perpendicular to the jet orientation and thus probably associated with an accretion disk (Torrelles et al. 1996), the proper motions of the H₂O maser in W3(H₂O) indicate that the maser emission traces the jet as well. For more details on H₂O masers and their origin I refer to the reviews by Garay & Lizano (1999); Kylafis & Pavlakis (1999).

5 Discussion

While we can study thermal jets in young massive star-forming regions at radio wavelengths, the Xray-regime appears to be far less promising. However, the most

Figure 4: The left panel shows the thermal radio jet observed toward Cepheus A HW2, the crosses mark H₂O maser positions (Torrelles et al. 1996). In the right panel we show the radio synchrotron jet observed toward W3H₂O, the arrows outline proper motion directions of H₂ masers in this field (Wilner et al. 1999)

interesting wavelength band for studies of molecular jets and outflows is the (sub-)mm band.

Recent years have brought tremendous progress, and in addition to the fact that massive outflows are ubiquitous phenomena, we now know far more details about the masses, kinematics and energetics. There has been a lot of discussion as to whether massive outflows are less collimated than their low-mass counterparts or not. High-spatial-resolution observations of various massive outflows have shown that very collimated jet-like structures do exist at the earliest evolutionary stages of high-mass star formation. Furthermore, comparisons of position-velocity diagrams with data from low-mass sources show that we observe similar kinematic structures for outflows of all masses, and that jet-driven as well as wind-driven models are necessary to explain all features. The statistical database of high-angular-resolution observations is still pretty poor, but the data are suggestive of a scenario where the collimation of massive outflows changes with time: at the earliest stages prior to forming an UCHII region collimated jet-like outflows appear to be present. As soon as the central protostar ignites and starts to form an UCHII region, wind-driven processes should come into play and contribute to the observed less collimated outflow morphology. Evolving further, the radiation of the central protostar starts destroying the accretion disk and collimated structures cannot survive anymore. In this scenario, it is no surprise that we did not detect a collimated outflow from a genuine O protostar yet because their evolutionary timescales are extremely short and it will be difficult to find and identify any such source.

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